Dedicated to innovation in aerospace

Modelling LH2 tank operations for hydrogen-powered aircraft using generalised thermal models

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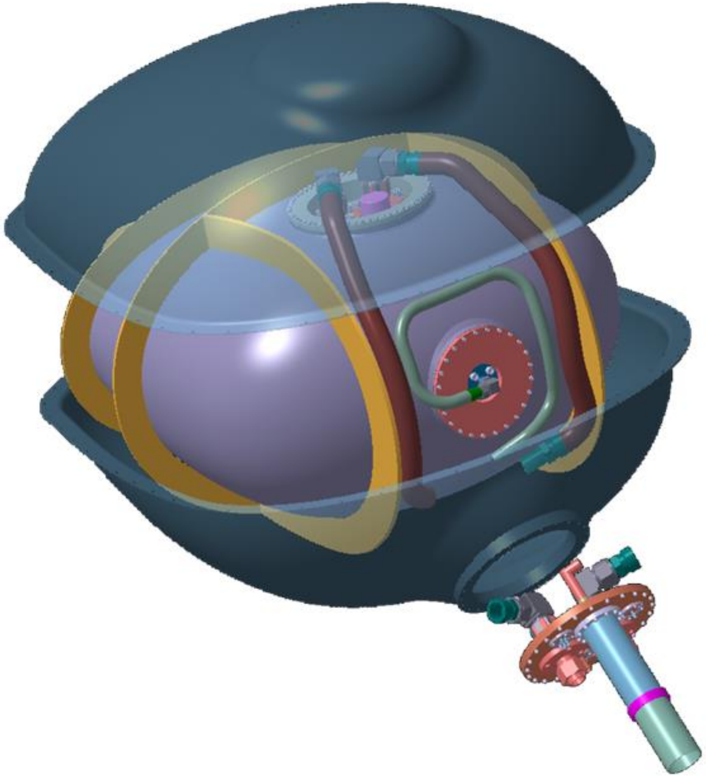
Today’s focus

- Show the value of single-node analyses for modelling LH2 tank operations
- Show methods for (i) TRL3 proof of concept testing and (ii) model validation, at component/subsystem-level for the functional operation of a LH2 tank
- Rethink the current-day design philosophy of LH2 tank thermal design for aircraft implementation

COCOLIH2T: LH2-tank design

- Conformal-shaped double-walled tank, insulated by vacuum and MLI
- Carbon-fibre composite laminate as base material for inner and outer tank
- Reduction of thermal bridging by advanced connector topology
- 1100 L, 4 bar(a), 57 kg LH2

COCOLIH2T CAD-design of LH2 tank
Courtesy of Collins Aerospace



ATR72-600
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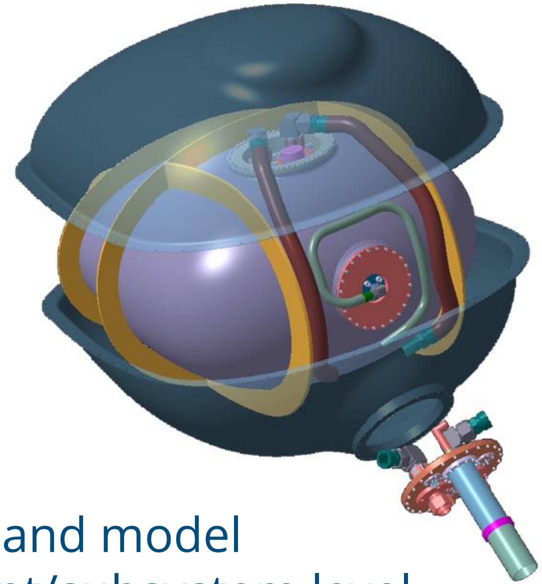
COCOLIH2T: TRL progression



TRL 2: Concept definition and coupon material testing

Now

TRL 3: Proof of concept testing and model validation at component/subsystem level

End of project

TRL 4: System thermal, mechanical, and functional validation with LH2

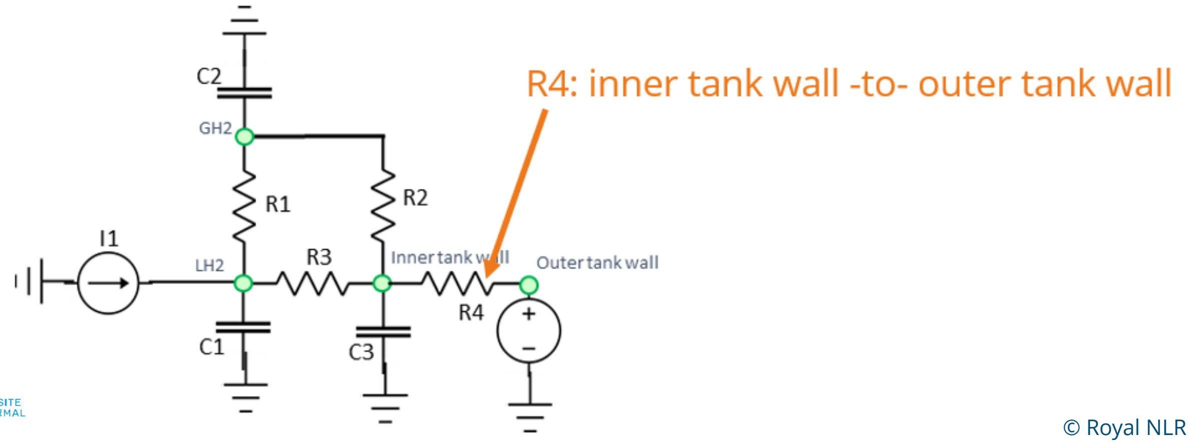
Towards EIS 2035

COCOLIH2T COMPOSITE CONFORMAL LIQUID H_2 TANK

Thermal design

Heat ingress via R4	Budget
MLI + vacuum *	20 W
H2 tubing incl. H2	10 W
Inner-outer tank connectors	2 W
Wires (incl. LH2 gauge)	1 W
Total	**33 W (dormancy max = 35 W)**

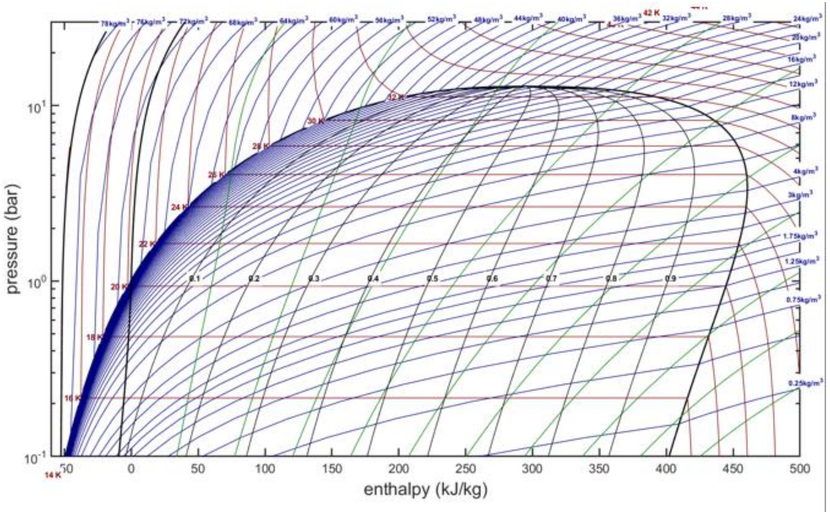
- 1D resistance network modelling
- Performance of MLI critical in R4
- *Note that H2 permeability through carbon-fibre composite inner tank deteriorates performance of MLI



p,h-diagram of Parahydrogen

- Single-node p,h analysis of tank two-phase state
- $\Delta h = T\Delta s + v\Delta p$
- Steady-state, applicable for first order analysis of dormancy, defuelling, and pressure management

- For Q = 35 W; m = 57 kg; V = 1.1 m^3
  → $t_{dormancy}$ = 23h55m



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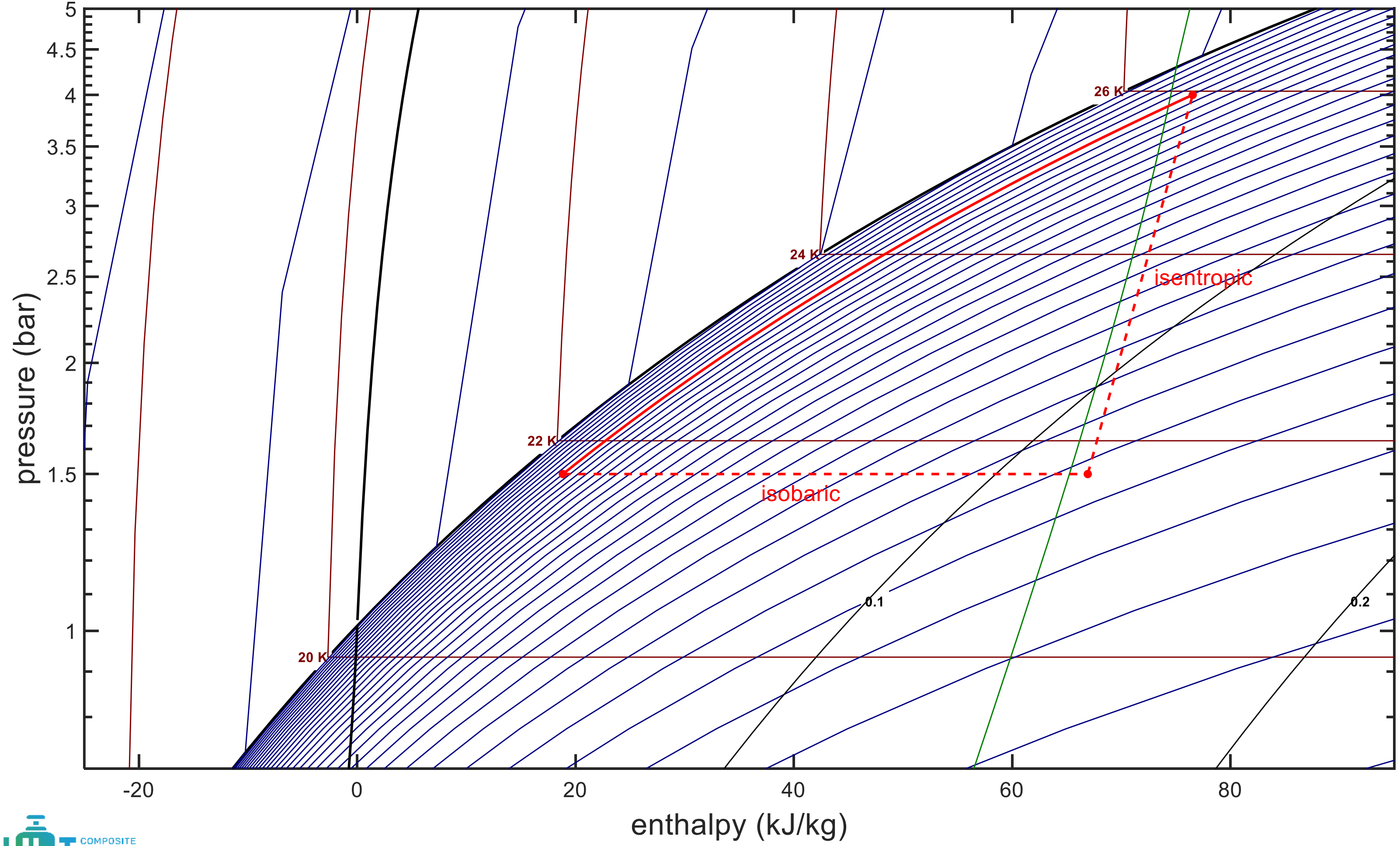
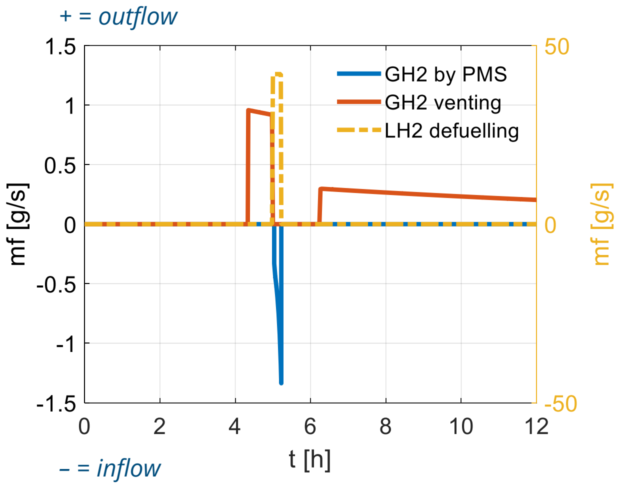
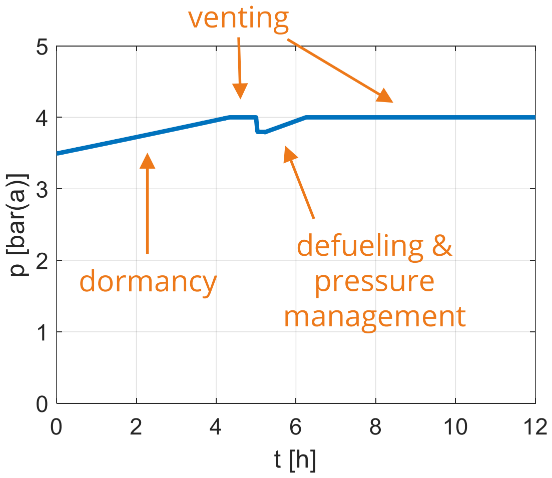


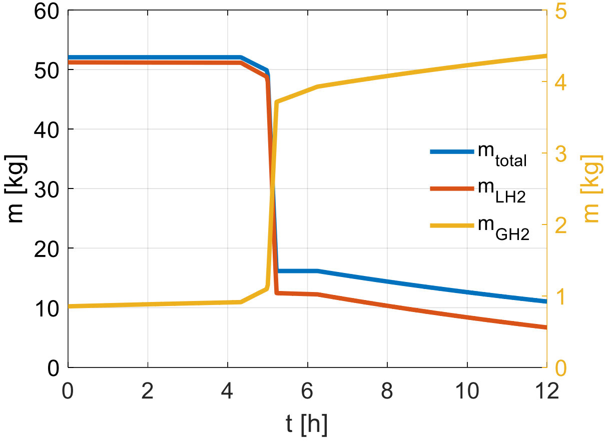
pressure (bar)
5
4.5
4
3.5
3
2.5
2
1.5
1
-20
0
20
40
60
80
enthalpy (kJ/kg)
26 K
24 K
22 K
20 K
isentropic
isobaric
0.1
0.2

Defuelling (42 g/s) and Pressure Management

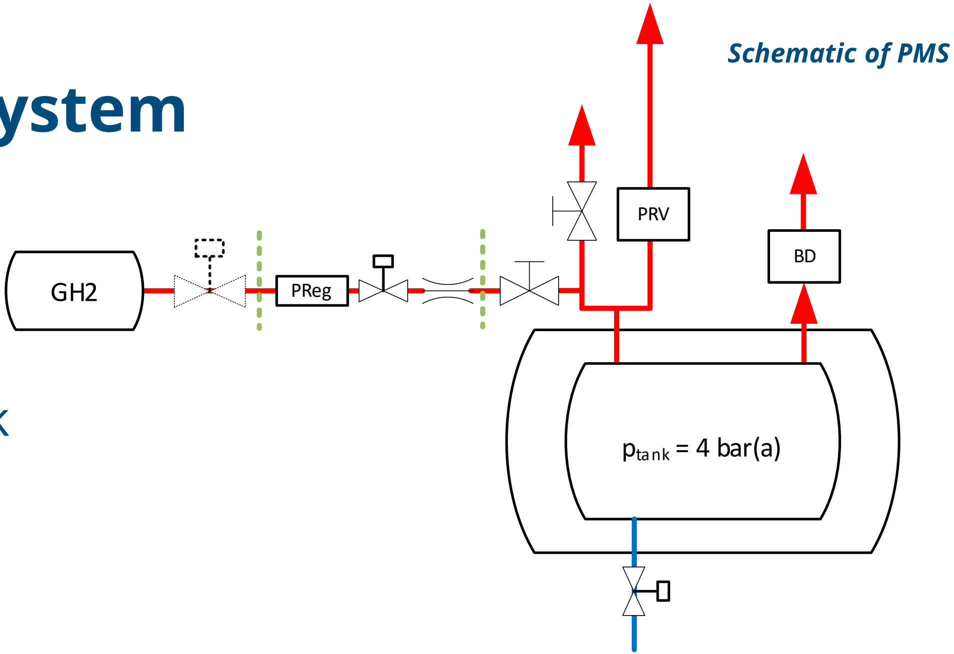
- Modelling operations using the single-node model
- Ambient temperature GH2 feed for pressurization







Pressure Management System



Various concepts:

- Heating element
  - Internal/external to inner tank
- **Warm GH2-feed into cold GH2**
- Warm GH2-feed into cold LH2
- Feedback line from LH2-line

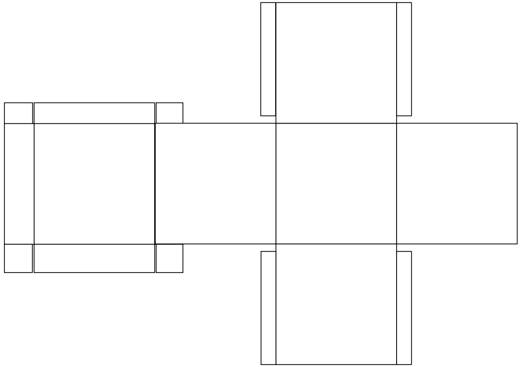
→ When LH2 defuelling out of tank is 42 g/s,
the GH2 pressurization flow only needs to be 0.2 g/s

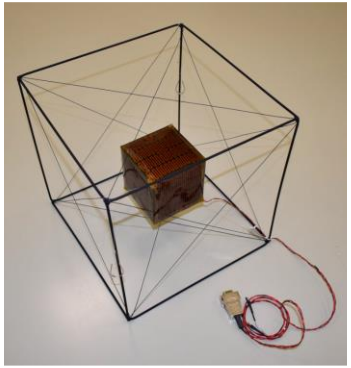
Refuelling operation [1]

- MLI temperature distribution
  - Validated internal temperature in a 10-layer pack of COOLCAT 2 NW [1] by heat flux testing in NLR's thermal vacuum chamber
  - T_{shroud} = [-150, -100, -50] °C
  - T_{heater} = [20, 100] °C
  - P_{heater} in order of 0-5 W

→ Model validation achieved

MLI testing
Courtesy of NLR





[1] product by Beyond Gravity GmbH

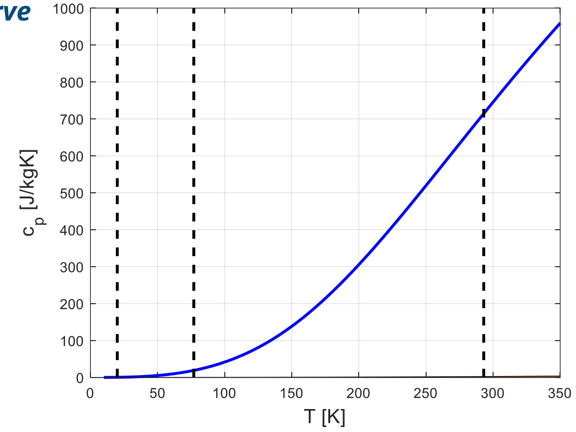
Refuelling operation [2]

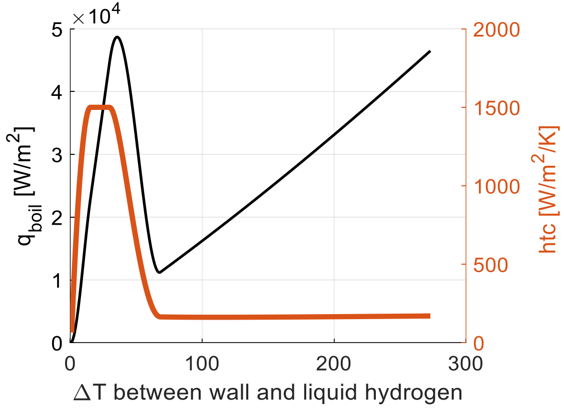
- c_p-determination of composite material;
  – Via molar mass, Debye temperature, and mean thermal energy expression:

$$\langle E \rangle = 9Nk_BT\left(\frac{T}{\theta_D}\right)^3 \int_0^{x_D} \frac{x^3}{e^x - 1}dx$$

- h-estimation by pool boiling relations
  – Leidenfrost effect plays significant role
  – A low through-plane thermal conductivity (k_3) of the inner tank wall results in overcoming Leidenfrost quicker

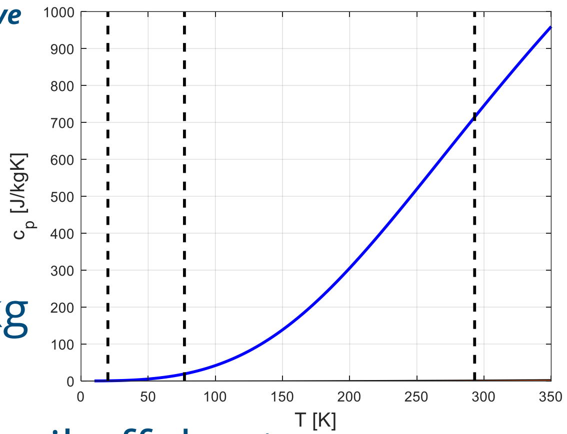
Composite $c_p(T)$ curve





Tank refuelling characteristics

Composite $c_p(T)$ curve



- Mass of LN2 needed for cooldown to 77 K: 199.5 kg
- LN2 refuelling will continue until 77 K is reached;
- After LH2-refuelling: in the order of 100g's of LH2 boil-off due to thermal mass of tank structure

	Filling	Composite inner tank	MLI COOLCAT 2 NW [1]	G10-CR structure	Total fluid use
Component		115 kg	6.3 kg	8.5 kg	
LN2	150 kg	46.1 kg	0.28 kg	3.1 kg	**199.5 kg**
LH2	57 kg	0.12 kg	0.02 kg	0.09 kg	**57.23 kg**

[1] product by Beyond Gravity GmbH

COCOLIH2T COMPOSITE CONFORMAL LIQUID H2 TANK

Arguments for aircraft LH2-tank design requirements as result of operation

- 2% boil-off/day has been considered as a design point in requirement phases. → However, dormancy simulations show that there's plenty of heat ingress budget for initial pressurization

- For early entry-into-service aircrafts, on-ground systems shall cover for boil-off during on-ground dormancy

- During flight operation, withdrawal of LH2 is a stronger enthalpy gain than the enthalpy gain by steady-state heat ingress

In conclusion

- The presented study shows the applicability of a single-node analysis for LH2 tank operations simulations
- This study has enabled the COCOLIH2T LH2-tank design to progress towards TRL4 demonstration at end of project
- A toolbox was developed for refuelling modelling, incl. a verified MLI-model, $c_p(T)$-curve of carbon-fibre composite laminates, and specification of a refuelling operation, using LN2 and LH2
- Lastly, the design philosophy of aircraft LH2 tank design was challenged

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Thanks for your attention!

See you at Univ. of Twente!

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